Field-based Coordination

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March 2010

Outline

- Part 1: What is Field-based Coordination
  - Definitions
  - General aspects of field-based coordination
  - Fields, self-organization, and stigmergy
- Part 2: Examples of Field-based Coordination in Nature
  - Gravitational systems
  - Flocking in birds and fishes
  - Wolves surrounding a prey
  - Morphogenesis
  - Modeling Fields
- Part 3: Applications of Field-based Coordination in Distributed Systems Engineering
  - Location-awareness
  - Motion coordination
  - Self-assembly
- Part 4: Programming Field-based Coordination
  - The TOTA Approach
  - Examples of TOTA applications
- Conclusions and Open Issues

Part 1

- What is Field-based Coordination

What is Field-based Coordination

- Field-based coordination is a physically-inspired indirect form of coordination
  - The space in which "agents" live is spread by sorts of force fields
    - E.g., gravitational fields, electromagnetic fields, chemical fields
  - Agents in their turn can contribute to spreading fields in space
    - E.g., the same as masses contribute to gravitational fields
  - Agents are affected in their activities by the locally perceived fields (type and strength)
    - E.g., the same as masses are attracted by gravitational fields
  - Fields are automatically updated to reflect the actual conditions
    - E.g., the same as gravity changes as planets move

What are “Agents” in Field-based Coordination

- Where talking about field-based coordination we will refer to the term “agent” to refer to
  - Any kind of autonomous entity situated in an environment
  - Sensing and effecting the environment via fields
  - Thus indirectly interacting with each other
- Examples
  - Animals
  - Software processes and software agents on a network
  - Mobile devices and sensor networks
  - Humans
  - Robots

What is “Environment” in Field-based Coordination

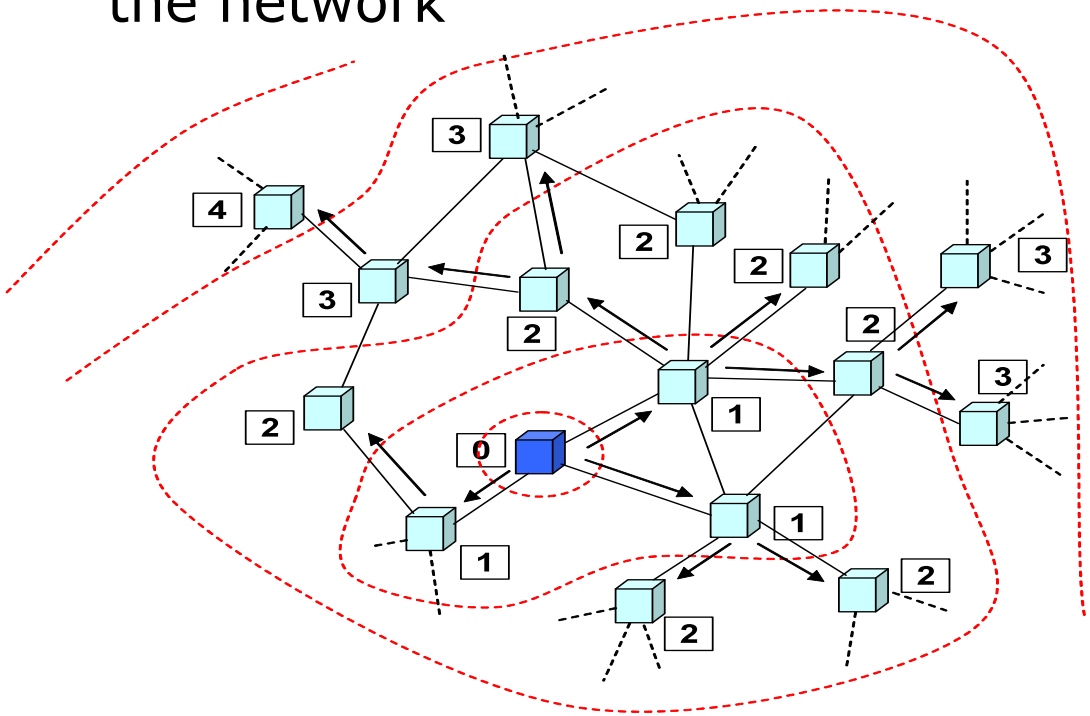
- When talking about “environment” in field-based coordination we generally refer to
  - The “space” in which agents execute
  - The “space” in which fields propagate
  - It is mostly an abstraction that assume actual meaning in actual examples
- Examples
  - A landscape in which animals live and interact
  - A network
  - A building in which humans and robots live

What are Fields?

- Assuming the presence of an environment
  - Fields are "distributed properties" of that environment
  - Describing "something" related to that environment in a distributed way
- Examples
  - The gravitational field is a property of space somewhat describing the structure of masses around
  - The pressure field is a property of the atmosphere describing the density of the air
- More in general, given
  - An metric environment *E* (i.e., an environment whose points can be somewhat mapped in terms of some system of coordinates **X**)
  - A field *F* can be defined as a function mapping a set of value over the coordinates of the environment $V=F(\mathbf{X})$, $\mathbf{X} \in E$

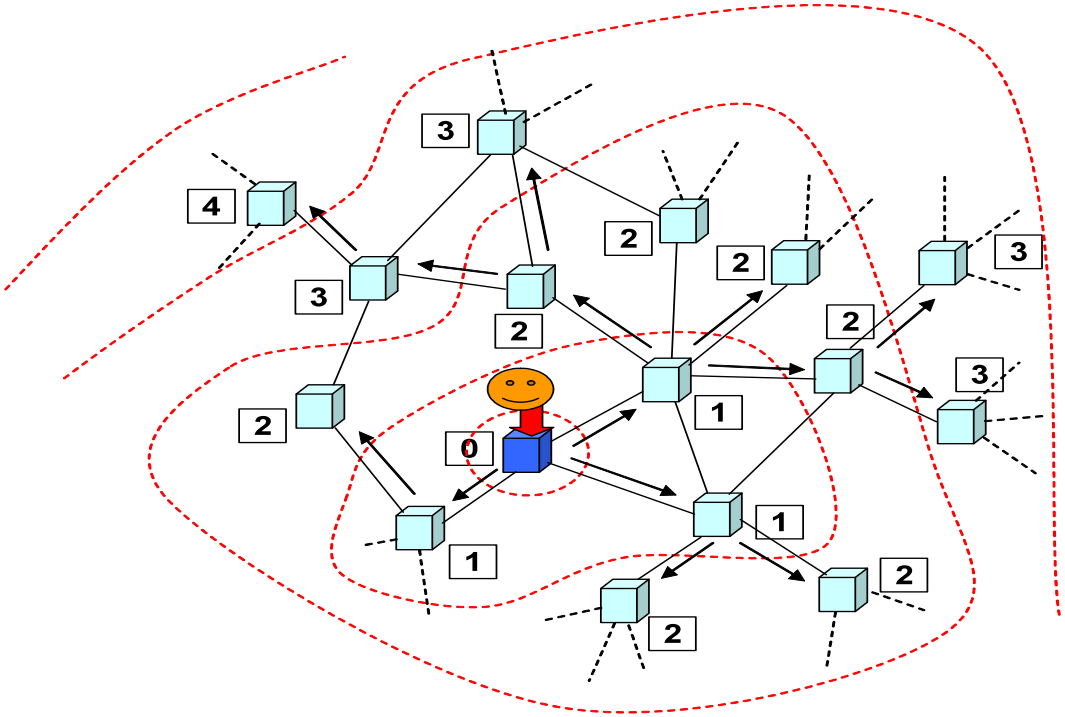
Example of a Field over a Network

- Given a specific node of a network
  - We can imagine having a field that spread from that node and
  - Propagates over the network with a local value that increases each hop while traveling the network



Spreading Fields

- There are several possibilities about spreading fields
  - Fields can be an intrinsic property of space, independent of the presence of agent (e.g. pressure in atmosphere)
  - Fields can be spread by agents, and different agents can spread different types of fields independently (e.g., a cry)
  - A field can be an aggregation of different fields spread by individual agents (e.g., gravity)

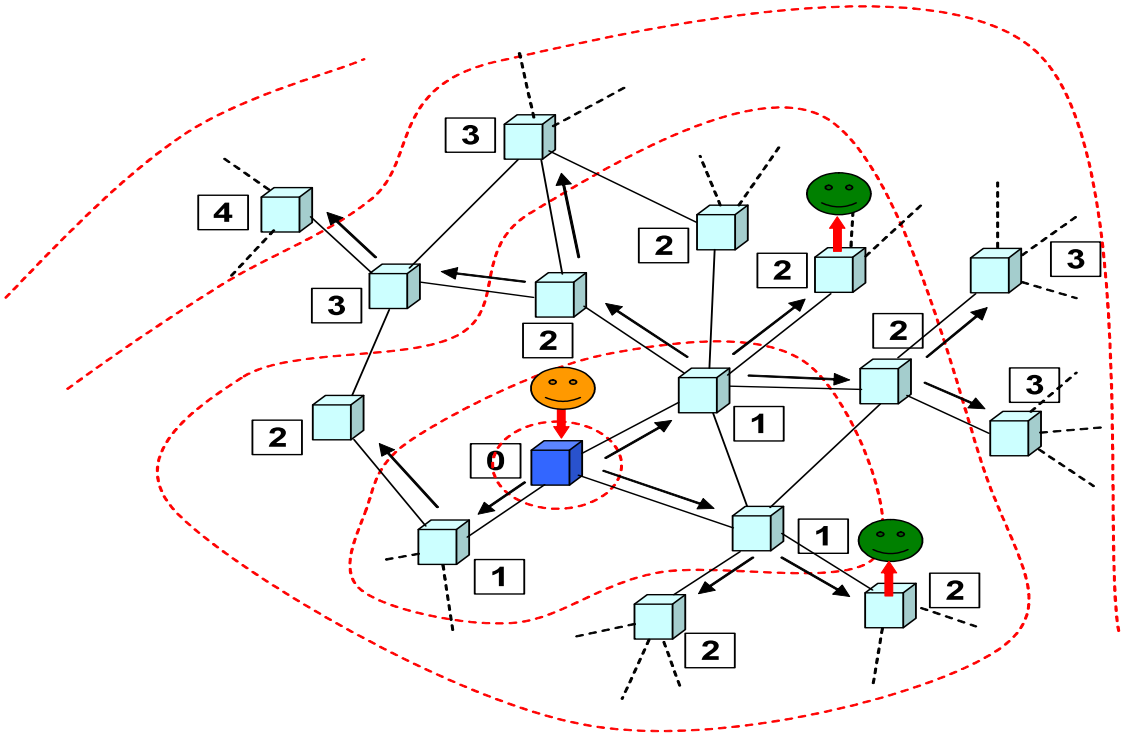


Sensing Fields (1)

- In general, in field-based coordination we assume (as in nature) only strictly local sensing capabilities
  - An agent can perceive the local value of a field, not the overall distributed structure of a field
  - At least, it can perceive the local gradient of the field (i.e., in which direction it grows and how must it grows)
- This is very important in distributed systems because
  - It does not require global communications
  - It promotes scalability (what the agent can sense is independent of the actual "size" of the environment)
  - It promotes decoupling (the agent sense the field but do not care about who or what causes it)

Sensing Fields (2)

- The same field, spread by the orange agent and sensed by two green agents
  - At different places
  - And so with different values



Fields and Context-Awareness

- To some extent, fields represent a way to spread contextual information over a network
  - The presence of mass in the case of gravitational fields
  - The presence of some data or of some agent doing something in the case of computational fields
  - The presence of an agent at a specific distance in the network
- Clearly, this is a partial information
  - I only know there is an agent somewhere at distance “3”
  - And if I can sense the gradient I can perceive the direction in which it is
- But it is obtained in a very effective way, at very low local costs!

Fields as Distributed Data Structures

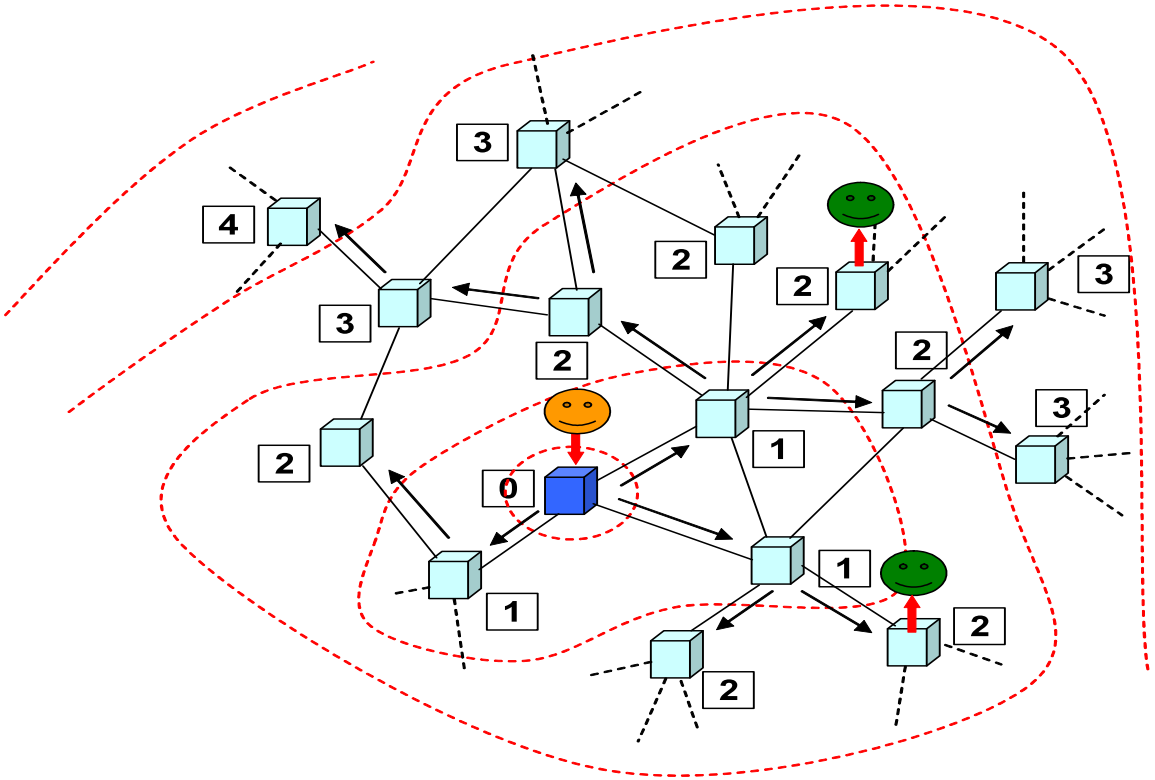
- To some extent, fields can be considered as a specific type of structured data
  - The structure is distributed
  - The same "information" is distributed on different regions of an environment
  - The information has a meaning that depend on the place on which it is perceived
  - And thus it varies to reflect in different regions the same meaning
- In the example of the network field
  - The meaning could be the distance from an agent
  - And thus the value has to change as the fields propagate farther from the source agent

Dynamics of Fields (1)

- Fields are expected to continuously reflect the actual state of what they represent
  - To reflect changes or movements of the originating agents
  - To reflect changes in the environment
- Examples
  - The gravitational fields of a star changes as it explodes or moves
  - The actual gravitational fields in a point of space depend on the position of all nearby masses
  - The structure of the network field should change if the structure of the network changes (due to, e.g., dismissing or mobility of nodes)

Dynamics of Fields (2)

- The node with the source agent moves
- And the field is updated



Dynamics of Fields (3)

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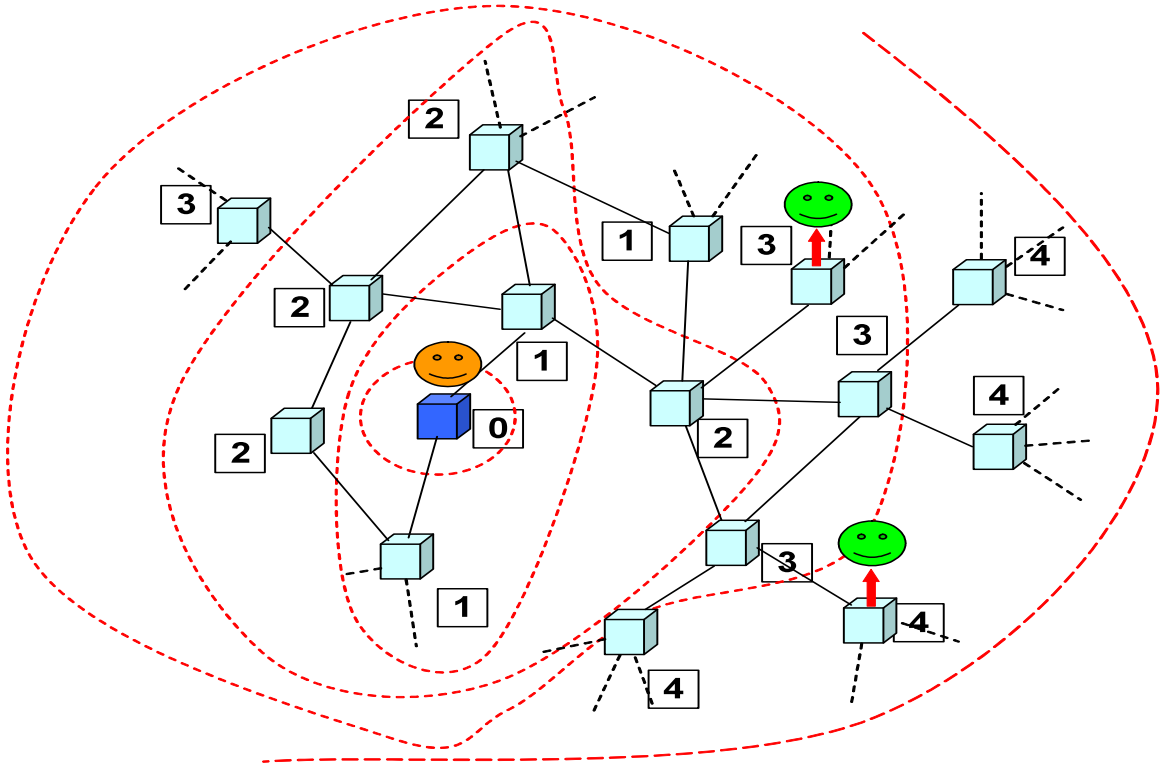


Fields and Adaptive Self-organization

- When agents rely on the local perception of fields for their activities
  - An agent locally perceives fields propagated by other agents
  - It may consequently change the structure of fields it own propagates
- This imply the intrinsic presence of feedback cycles
  - Which could be positive
  - Or negative
  - And which in any case we already know are the basic ingredients for adaptive self-organization
- Adaptive self-organization with fields
  - Adaptivity because fields changes to reflect changes in the environment (fields represent dynamic contextual information)
  - Self-organization because fields are a form of stigmergic coordination

Field-based Coordination and Stigmergy

- Field-based coordination is a specific type of stigmergic coordination
  - It is an indirect form of coordination
  - Fields represents property of the environment
  - Agents can affect the environment by spreading fields
  - Agents are affected by the environment, i.e., by the fields that are in it
- We will see that pheromones and fields are strictly related
  - After all, pheromones can be considered as sorts of "slow" fields
  - Thus, we will be able to implement pheromones with fields
  - Sometimes, the distinction between pheromones and field will be rather blurred

Part 2

- Field-based Self-Organization in Nature
  - And field modeling…

Gravitation, of Course…

- Well, gravity is field-based coordination
  - Is there self-organization?
- Yes, and indeed gravitational system exhibits all the possible status of dynamical systems
  - Equilibrium
    - All masses collapse into a single mass
  - Periodic Cycles
    - The regular orbiting of a mass around another
  - Self-organization ("edge of chaos")
    - Consider the asteroids belt
      - It is rather "stable" and exhibit an overall organized, persistent, and adaptive, "shape"
      - Still, the movement of asteroids within is by no means periodic of stable
      - It is a system at the edges of chaos
  - Chaos (e.g., clusters of isolated asteroids)
    - Indeed, even a small number of isolated asteroids of similar mass moves around each other in a chaotic way

Flocking

- Birds and Fishes, as well as several other species, move in groups in a rather organized and ordered way
  - There is no leader in general
  - There is not agreement
  - Animals per se are not so intelligent
- So how does it work such expression of swarm intelligence?
  - Very similar to humans escaping fires

Mechanisms of Flocking

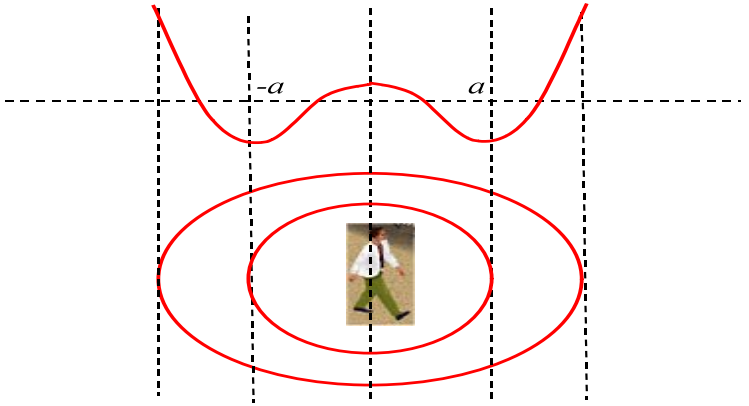
- Two possible explanations, same results

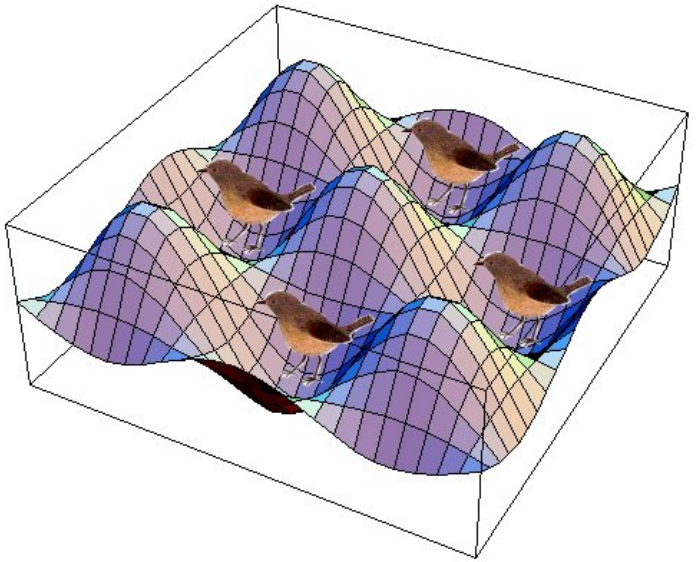
- 1. They do so because they want to stay together
  - possible explaining mechanism for each bird
    - Target closest bird
    - Get at a specific distance from it
    - Match its speed and direction
  - But this assumes a sort of mimicking capabilities in bird

- 2. They do so because in that way their movements are more effective (as a cyclist knows well!)
  - Possible explaining mechanism for each bird
    - Just fly
    - Trying to always stay in the zone of lower pressure
  - This is a mechanism of field-based coordination
    - The pressure field of birds as they fly
    - Influences the fly of other birds
    - Ending up in organized patterns of movement

Field-based Flocking

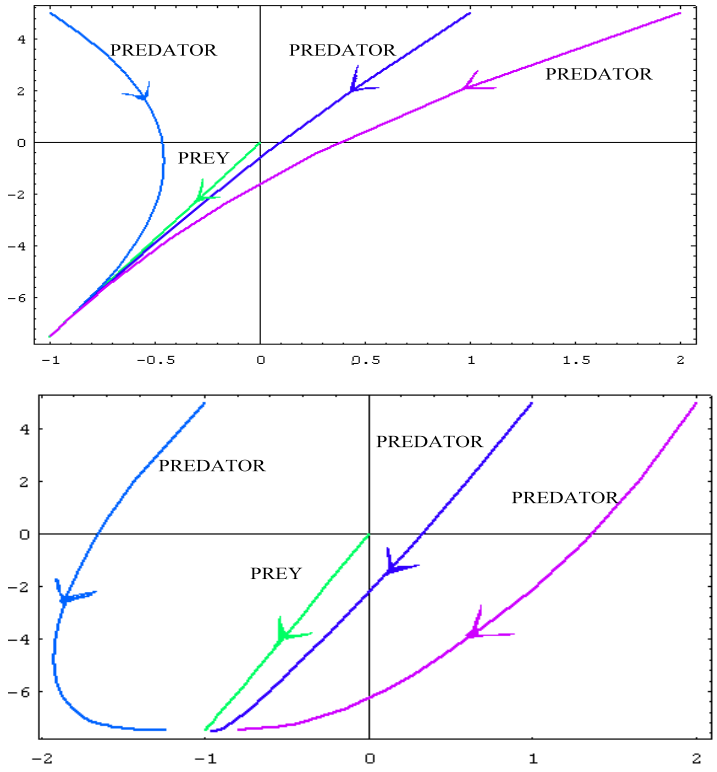
- The pressure field generate by each bird has a form like that:
- A bird close to another bird will try to stay in the minimum
  - i.e., will be attracted by the field
- Overall, when birds get flying together, they will end up in regular grid formations
- See the NetLogo simulation





Sheep Surrounded by Wolves

- When wolves go preying and see a e.g., sheep
  - They do not simply try to capture it in a greedy way
  - Rather they circumvent the prey
  - And leave it not way of escaping
- Is this wolves' intelligence or there are swarm intelligence mechanisms behind?
  - The behavior is isomorphic to that of insects collectively carrying big objects
  - So it is likely to be a swarm intelligence phenomenon



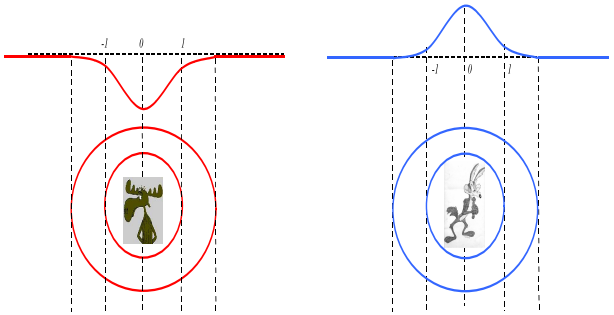
Mechanisms of Surrounding

- Very simple indeed
  - Wolves are attracted by the sheep
  - But repel each other (because of competition)
  - The result is surrounding!
- This can be easily modeled in terms of fields
  - Attractive force fields: the wolves tries to reach the minimum of a force field originated by the sheep, and having its minimum by the sheep
  - Repulsive force fields: the wolves tries to reach the minimum of the aggregated force field generated by wolves, and having its minimum at infinity
  - Of course, the sheep fields must dominate!
- Ah, and obviously
  - It is expected that the sheep will try to escape, being repelled by wolves' fields

Field-based Surrounding

- The Sheep field and the wolves fields
- The resulting force that drives wolves movement is something like:

FORCE = sheep_field – sum(wolves_fields)



Modeling Field-based Coordination

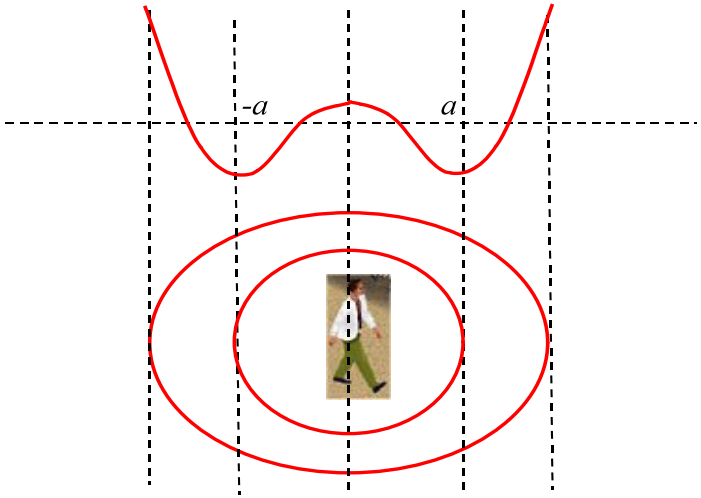
- In the previous examples, fields act as forces attracting/repelling animals
  - Coordination, in this case, is related to motion and position
  - **MOTION COORDINATION**
  - Fields influence the relative positions and movements of animals in the environment
- In these case, it is possible to model field based coordination in terms of a simple dynamical system in which:
  - Fields are modeled as function of the position of the sources (i.e., of the animals but more in general of the agents)
  - The next position of animals/agents is determined by the composition of the fields that they sense at the current time in their current positions
  - This is simply a system of differential equations…

Modeling Fields

- Let's express field as a function of time and space (i.e., position of the source agent)
  - E.g. the Flock field

$$d = \sqrt{(x - X_B^i)^2 + (y - Y_B^i)^2}$$

$$FLOCK_i(x, y, t) = d^4 - 2a^2 \cdot d^2$$



The Coordination Field

- In general, agents do not direct their action based on a single field, but based on a combination of locally perceived field
- If the specific combination of these fields, that we call ***coordination field*** *(CF)* that determines where the agent will go
- In the case of flocking, any agents tries to reach the minimum of all the locally perceived FLOCK fields
- Thus is operate based on a min combination of local FLOCK fields

$$CF(x_1, x_2, \ldots, x_n, t) = f(FIELDa, FIELDb, \ldots, FIELDn)$$

$$CF(x, y, t) = \min(FLOCK_i(x, y, t) : i = 1, \ldots, n)$$

The Evolution Equations (1)

- Thus, the laws governing the movement of an agent *i* along the *xj* direction are in the form below
- Where the spatial derivative of the coordination field expresses the fact that an agent follows the gradient of the coordination field

$$\frac{dx_j^i}{dt} = v \cdot \frac{\partial CF_i(x_1, x_2, \ldots, x_n, t)}{\partial x_j}\left(x_1^i, x_2^i, \ldots, x_n^i, t\right) \quad j = 1,2,\ldots,n$$

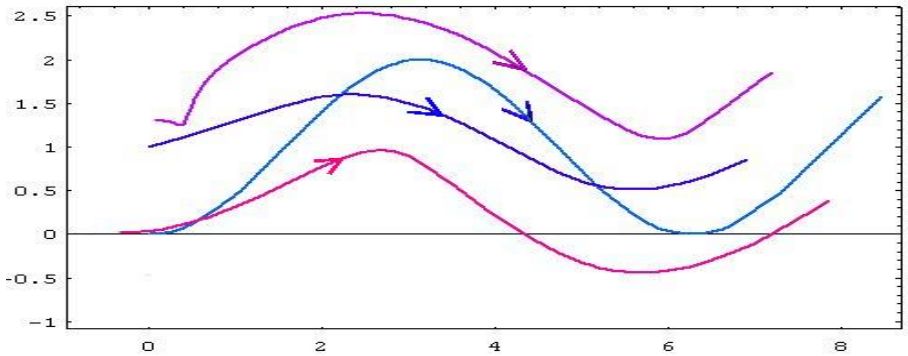
The Evolution Equations (2)

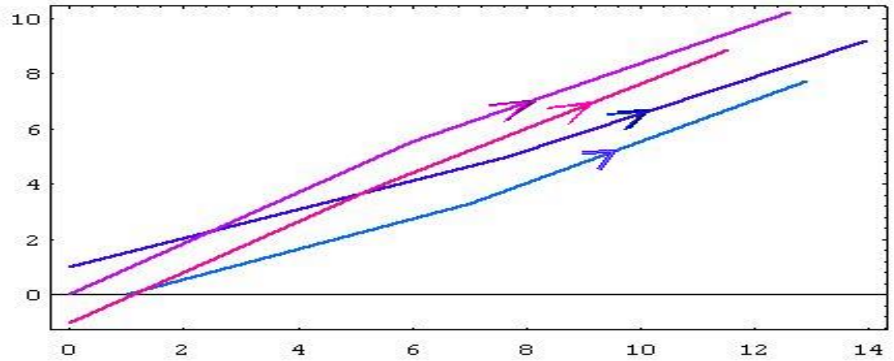
- Thus, for an example in the 2-dimensional case, the evolution of the flocking behavior for an agent *i* can be described by the following system of differential equations

$$\begin{cases} \dfrac{dx_i}{dt} = -v \dfrac{\partial \min\left(FLOCK_1, FLOCK_2, \ldots, FLOCK_n\right)}{\partial x}\left(x_i, y_i\right) \\ \dfrac{dy_i}{dt} = -v \dfrac{\partial \min\left(FLOCK_1, FLOCK_2, \ldots, FLOCK_n\right)}{\partial y}\left(x_i, y_i\right) \end{cases}$$

Integrating the Equations

- Once the equations are defined
  - We can write them for each agent
  - And initialize them with the initial positions of the agents
  - Obtaining a global set of related differential equations
- The equations can be numerically solved by mathematical software tools to see the evolution of the system (i.e., the trajectories of agents in space)
  - Aside two examples for a flocking system with 4 agents in 2-d
  - With different initial conditions





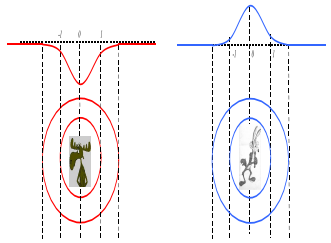
Modeling Surrounding (1)

- The FIELD of wolves (pred)

$$FIELD_i^{pred}(x,y,t) = 1 + k_p - k_p e^{-h_p\left(\left(x-X_P^i\right)^2+\left(y-Y_P^i\right)^2\right)}$$

$$k_p, h_p > 0; \quad 1 + k_p - k_p e^{-2h_p} \approx 1$$

- The FIELD of sheeps (prey) is simply the opposite of that of wolves…



Modeling Surrounding (2)

- Coordination field of wolves (*pred*)

$$CF_i^{pred}(x,y,t) = FIELD^{prey}(x,y,t) + \sum_{j=1, j\neq i}^{n} - FIELD_j^{pred}(x,y,t)$$

- Coordination field of sheeps (*prey*)

$$CF^{prey}(x,y,t) = \sum_{i=1}^{n} - FIELD_i^{pred}(x,y,t)$$

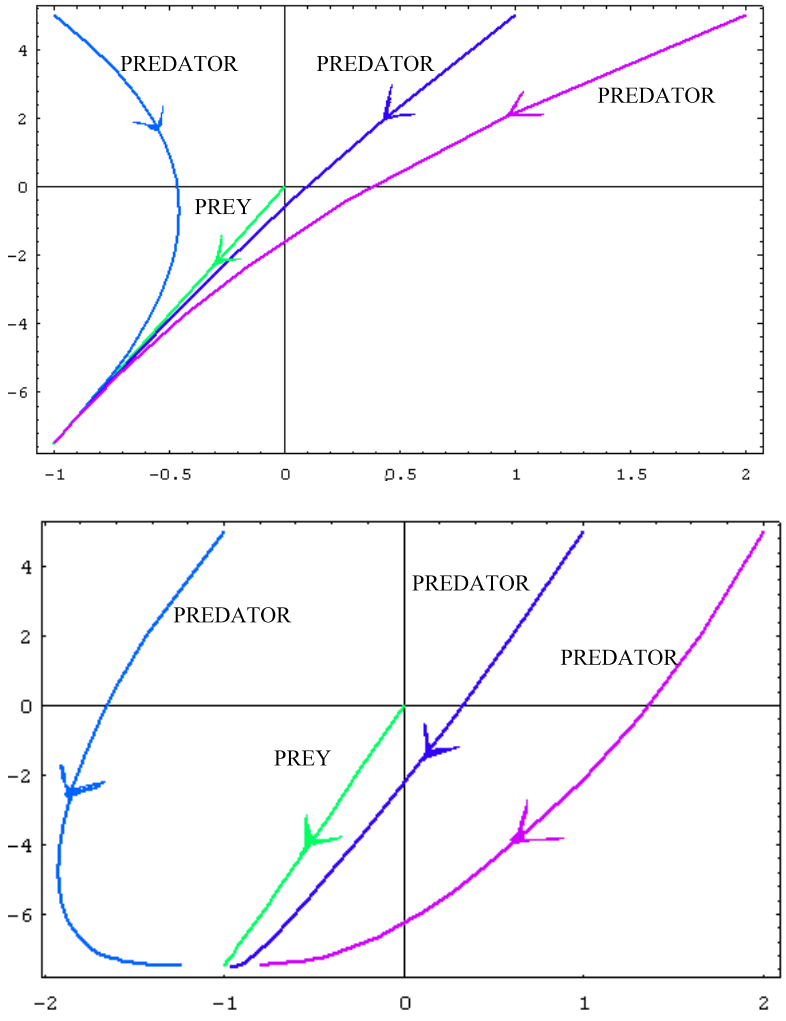
Modeling Surrounding (3)

- The overall equations

$$
\begin{cases}
\dfrac{dx^{prey}}{dt} = -v^{prey}\dfrac{\partial CF^{prey}(x,y,t)}{\partial x}\left(x^{prey}, y^{prey}\right) \\
\dfrac{dy^{prey}}{dt} = -v^{prey}\dfrac{\partial CF^{prey}(x,y,t)}{\partial y}\left(x^{prey}, y^{prey}\right) \\
\dfrac{dx_i^{pred}}{dt} = -v^{pred}\dfrac{\partial CF_i^{pred}(x,y,t)}{\partial x}\left(x_i^{pred}, y_i^{pred}\right) \quad i = 1,2,\ldots,n \\
\dfrac{dy_i^{pred}}{dt} = -v^{pred}\dfrac{\partial CF_i^{pred}(x,y,t)}{\partial y}\left(x_i^{pred}, y_i^{pred}\right) \quad i = 1,2,\ldots,n
\end{cases}
$$

Modeling Surrounding (4)

- The Integrated equations (compared with the no-surrounding case)



Why Modeling?

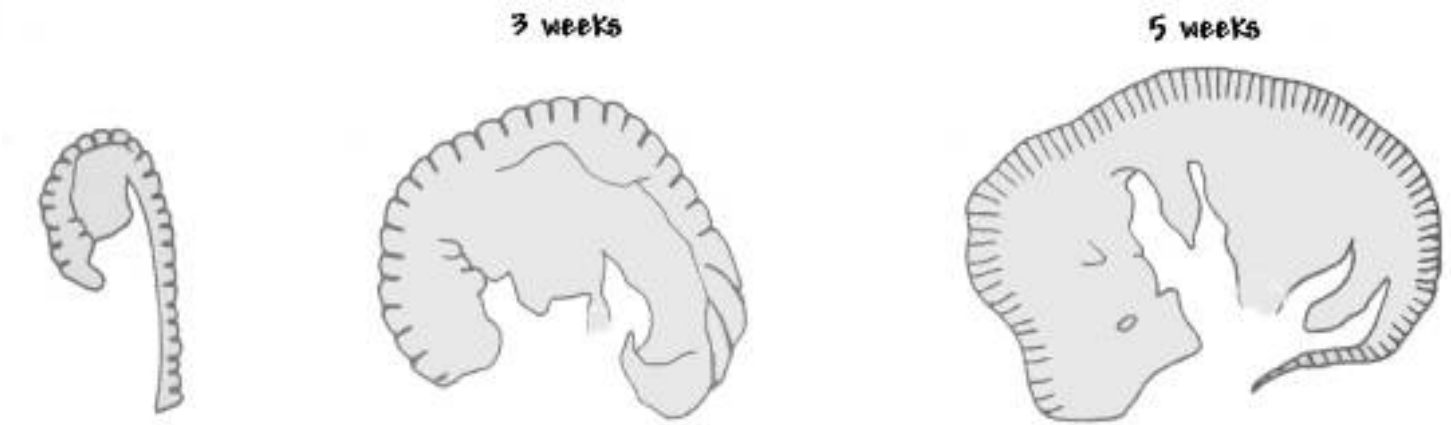
- It can be useful to understand, prior to developing a system, and prior to build a simulation, if an approach make sense
  - The mathematical simulation, even if unrealistic, or developed with a limited number of agent, can outline specific problems of a solution
- In any case, this must be coupled with simulation, including a larger number of agents

Motion vs. Activity

- So far, in the examples, fields have been used to determine the movement of agents
  - Pure motion coordination
  - The reaction of agents in perceiving fields was simply that of following the gradient of the fields
- However, field-based coordination may be more general
  - The perception of a specific field with a specific value by an agent
  - Can cause it to change its internal state
  - Can make it react to emit other types of fields or to inhibit the propagation of some fields
- In other words, fields can be used to enforce coordination of activities other than of motion
- For example, in morphogenesis…

Morphogenesis

- Morphos + Genesis = Shape Birth
  - The process by which something grows into a specific shape
- This is definitely one of the biggest open issues in science
  - How an embryo grows?
  - How cells understand how to differentiate each other?
  - How can they understand where to grow and when to stop?
- What is being understood is that a field-based coordination model is behind all (most of) that



Morphogen Gradients = Fields

- Cells emit chemicals
  - Which diffuse from cell to cell
  - As in the example of the field spreading in a network hop by hop
- The behavior of a cells, that is
  - The activation/deactivation of specific genes and – thus – the type of cell it has to become and the way it must reproduce
  - The type of chemicals that the cell, in its turn has to diffuse
- Is determined by the perceived concentration of morphogen gradients
  - The same as in field-based coordination the actions of an agent are determined by its local perception of field

Fields vs. Pheromones

- Pheromones are something that gets deposited in an environment
  - And there rest
  - Slowly diffusing
  - And slowly evaporating
- Fields, on the other hand, are something that exists because some entities are propagating them
  - They exists until they gets propagated
  - They immediately change when the conditions of propagation change
- Clearly, it is possible to conceive a field
  - With a very very slow propagation
  - With a very very slow reaction time in changing
- In that case, the field would become a pheromone
  - i.e., it is possible to model pheromones in terms of "slow" fields
- In any case, it is important to note that for both fields and pheromones
  - The **environment plays a vital role** in sustaining propagation and updates

Part 3

- Applications of Field-based Coordination

The Applications are Various…

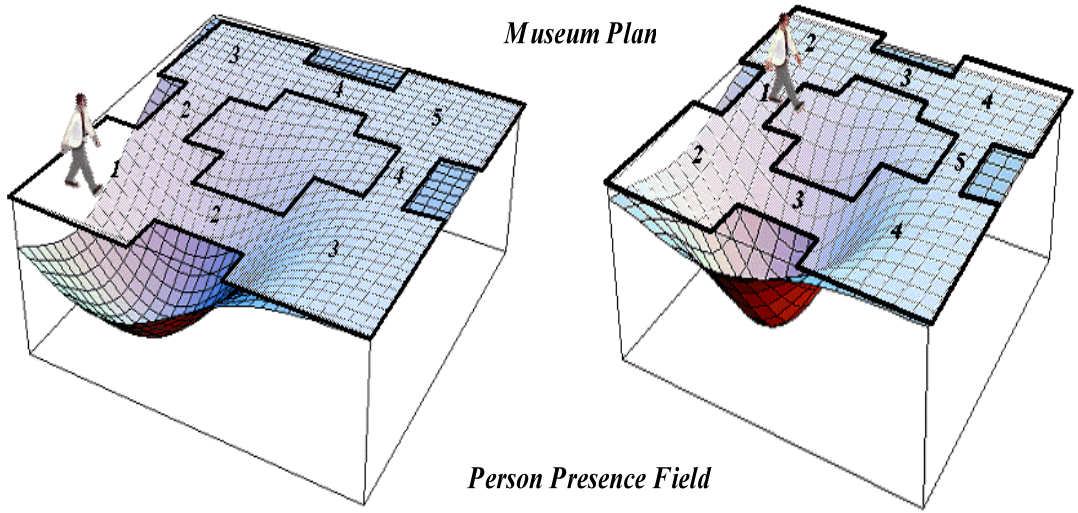
- Location-awareness
  - As a way to distribute and access contextual, location-dependent, information
  - In pervasive and mobile computing scenarios, as well as in sensor networks
- Motion Coordination
  - For mobile users, robots, or software agents
- Videogames
  - Using fields to drive characters
- Self-assembly
  - As a way to mimic morphogen gradients and produce self-assembly artifacts in which parts can self-differentiate
  - This will be dealt with separately, in another lecture

A Scenario: a Big Museum

- A big museum, such as the Louvre
  - Difficult to explore (where the hell is Mona Lisa?)
  - With a structure and topology often varying (due to temporary exhibitions or restructuring)
  - With a lot of information to access about art pieces
- Let us assume that
  - There is a network running in the museum whose topology mimic the topology of the museum (if not, the museum topology can be simply mapped as an overlay over the physical network)
    - This could also be an-hoc wireless network, to avoid the costs and the damages of wiring
  - Each piece of art has an internal device with info about it, integrated in the network
  - Each users and tourist guide has a PDA via which to access the network from the closest access point
- The scenario, in any case, is representative of a wider range of distributed applications…

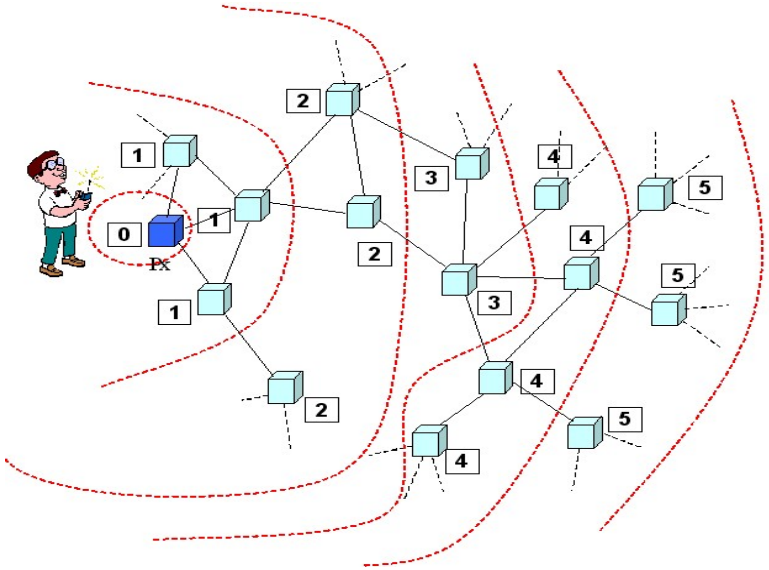
Location-awareness in the Museum

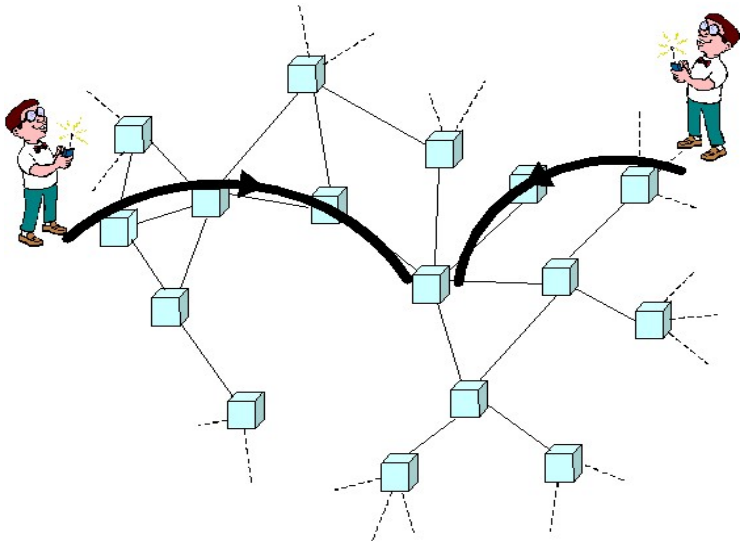
- Fields, propagated in the museum by tourists, or be piece of arts, or by museum guars, can be used to have
  - Tourists discover where a specific piece of art is
  - Tourists and Guards discover where other tourists/guards are
  - Etc.
- To this end, we can assume that each tourist and each guards
  - Diffuse a PERSON PRESENCE field, propagating in the museum network with an hop-increasing value, and having also as a content the ID of the person



Discovering Other People

- Based on the PERSON PRESENCE field, any user can simply
  - Perceive the corresponding field (with the specific ID) to understand distance and direction
  - Eventually, decide to follow the field to reach that person





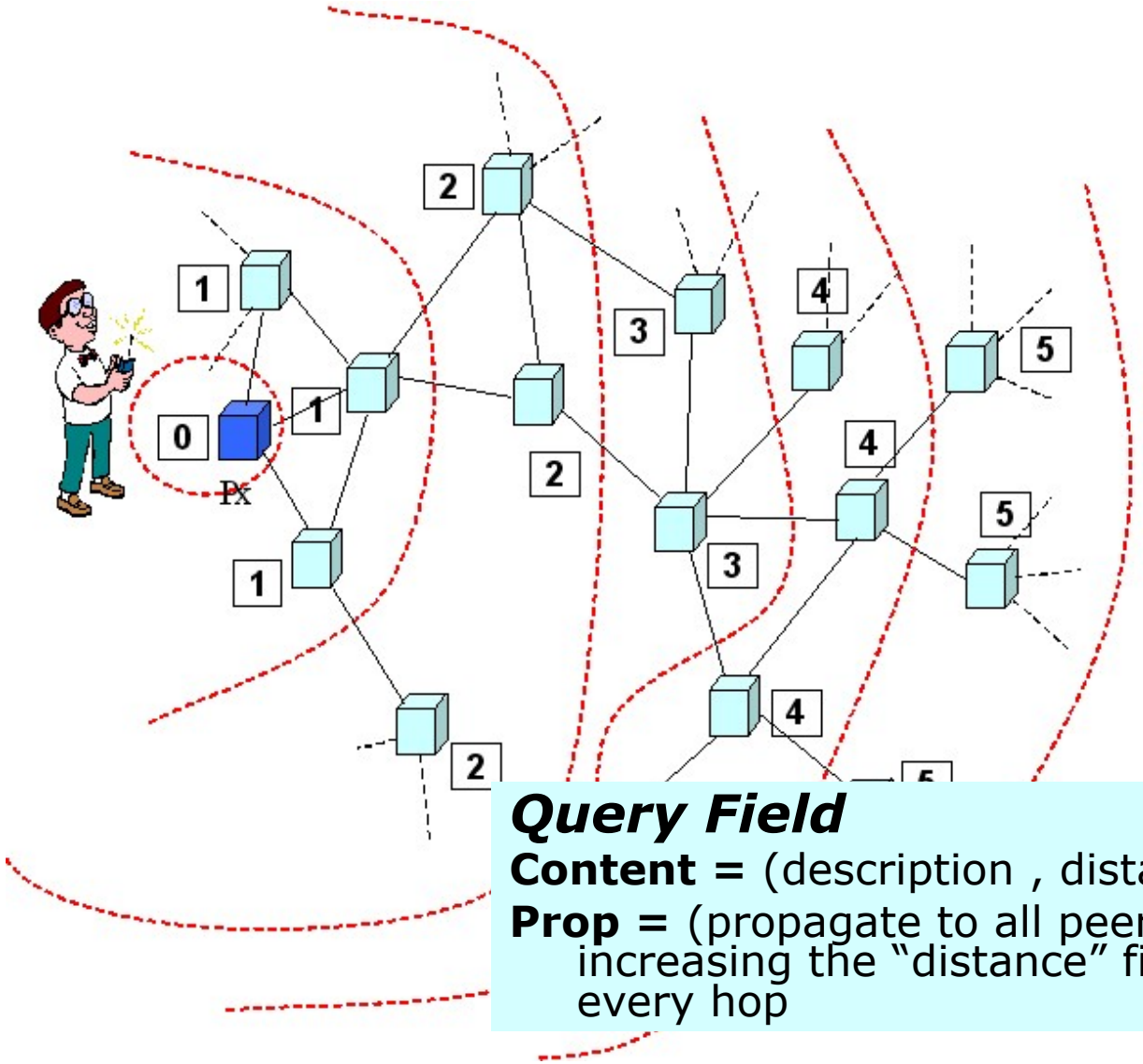
Discovering Pieces of Art (1)

- If each piece of art diffuse a similar field
  - Any person can locally read the location of that piece of art
- When a person is interested and reads the local field of a specific piece of art
  - Can eventually send a message-field to that piece of art to discover further information
  - The message field propagates by following downhill the field of the piece of art, and will reach it as a ball down a surface
  - When the piece of art receive the message field, can react by sending back to the user information

Discovering Pieces of Art (2)

- As an alternative solution
- To avoid pieces of art diffuse their fields in the whole museum, one can think at
  - The pieces of art have no fields diffused
- But can react to "Query fields" diffused by users
  - When a users wants to know something about a piece of art
  - Spread a query field that increase hop-by-hop as it travels
  - The query field reach the specific piece of art
  - Which react by spreading and "Answer field" that follows downhill the query until it reaches back the user

Where is Mona Lisa?
Propagate a Query Field

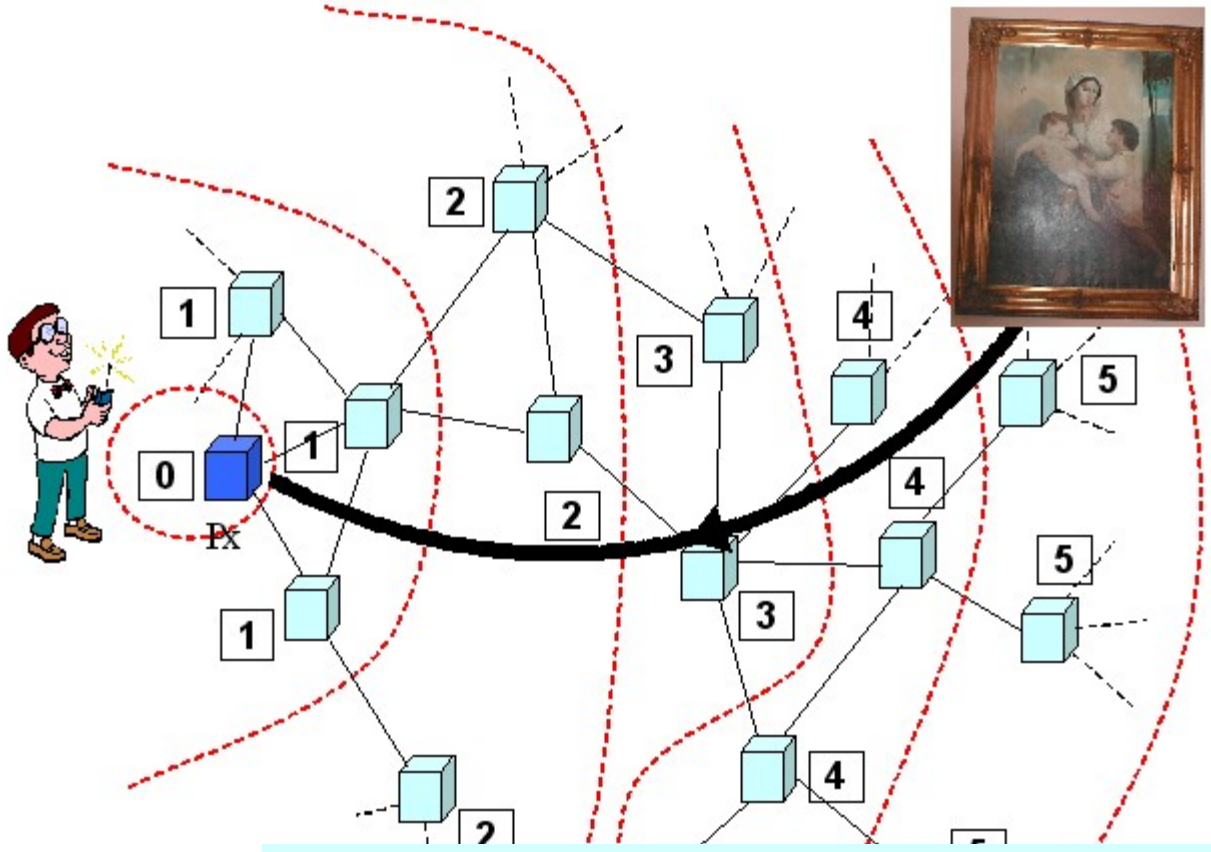


Query Field

Content = (description , distance)

Prop = (propagate to all peers hop by hop, increasing the "distance" field by one at every hop

Where is Mona Lisa?
The Answer Follows Query Field Downhill



Answer field

Content = (description, location, distance)

Prop = (propagate following downhill the "distance" of the associated query field, incrementing distance value by one at every hop)

Location-dependent Computing

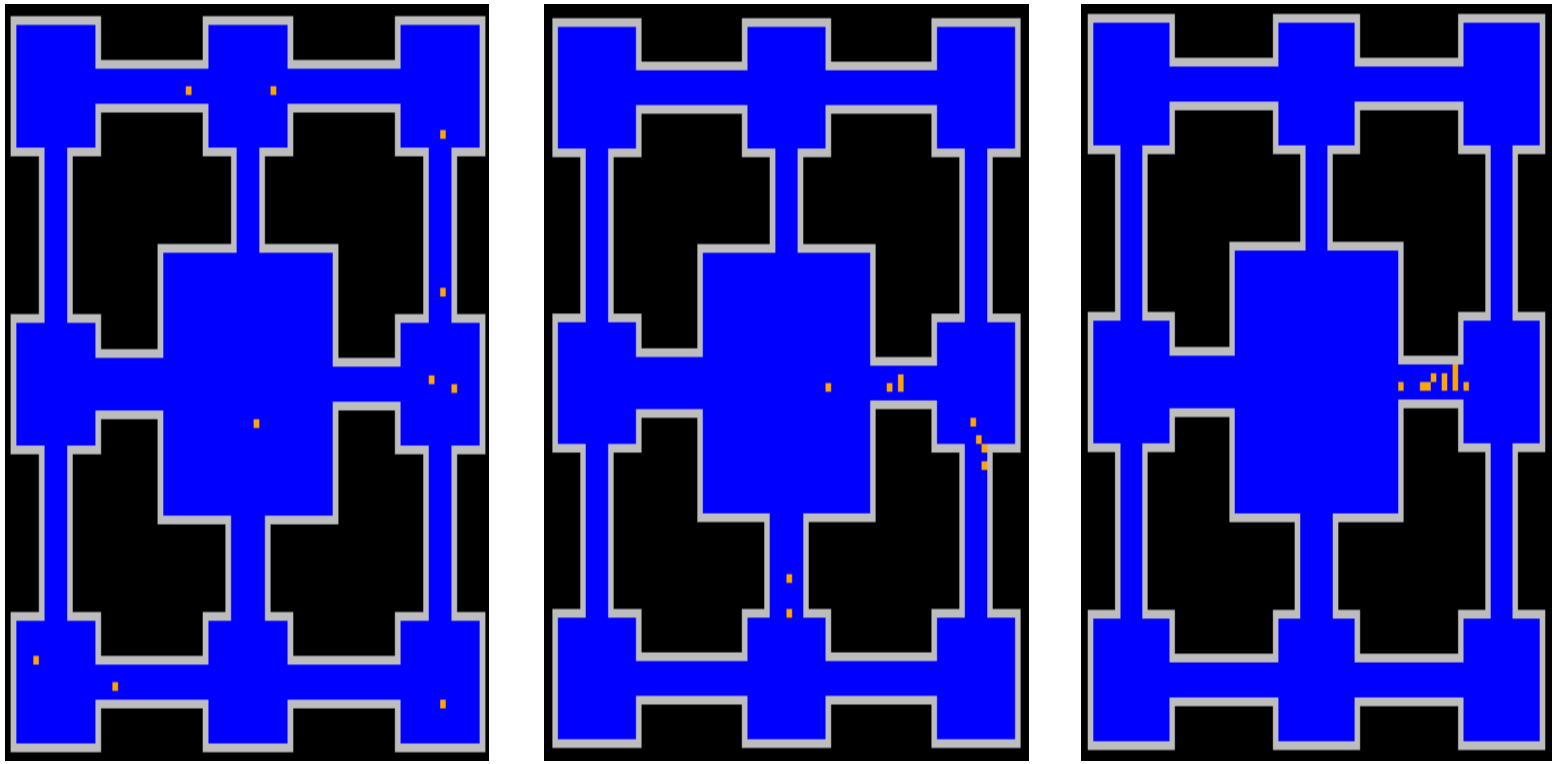
- In general, one can think at
  - Limiting the propagation of fields at specific distances
  - Directing the propagation in specific directions
- In that way, it is possible to
  - Search information in specific locations
  - Avoid being discovered from “too far”
  - Very useful in mobile and ubiquitous computing
- Example, as a tourist in a big town who ask the wireless city network for good chinese restaurants, I want to know about close restaurants, not about all restaurants in other – far – parts of the town

Motion Coordination

- By using the introduced PERSON PRESENCE field, one can think at coordinating the activities of tourists and guards, as they move in the museum
  - Meeting at a specific place, using PRESENCE FIELDS as gravitational fields (the meeting place will end up being the center of gravity, minimizing global efforts for meeting)
  - For guards, finding a children lost in the museum, or a thief using PRESENCE FIELDS to implement
  - Moving in formation (e.g., for guards) using FLOCK fields similar to that of flocking in birds
- What is interesting is that the resulting behavior is extremely adaptive
  - There is no need to know a priori the map of the museum
  - It is the propagation of fields that automatically adapt to the map
  - And enables any form of motion coordination, in an adaptive and environment independent way

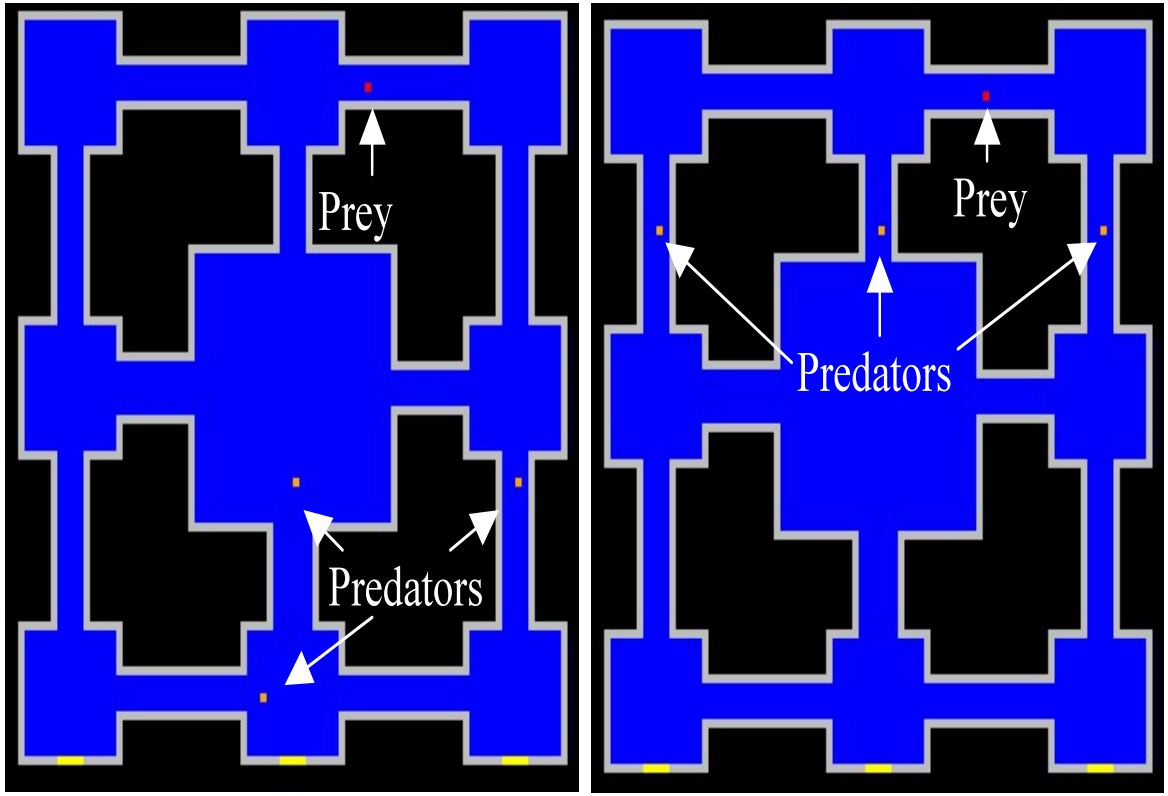
Examples of Motion Coordination

- Meeting



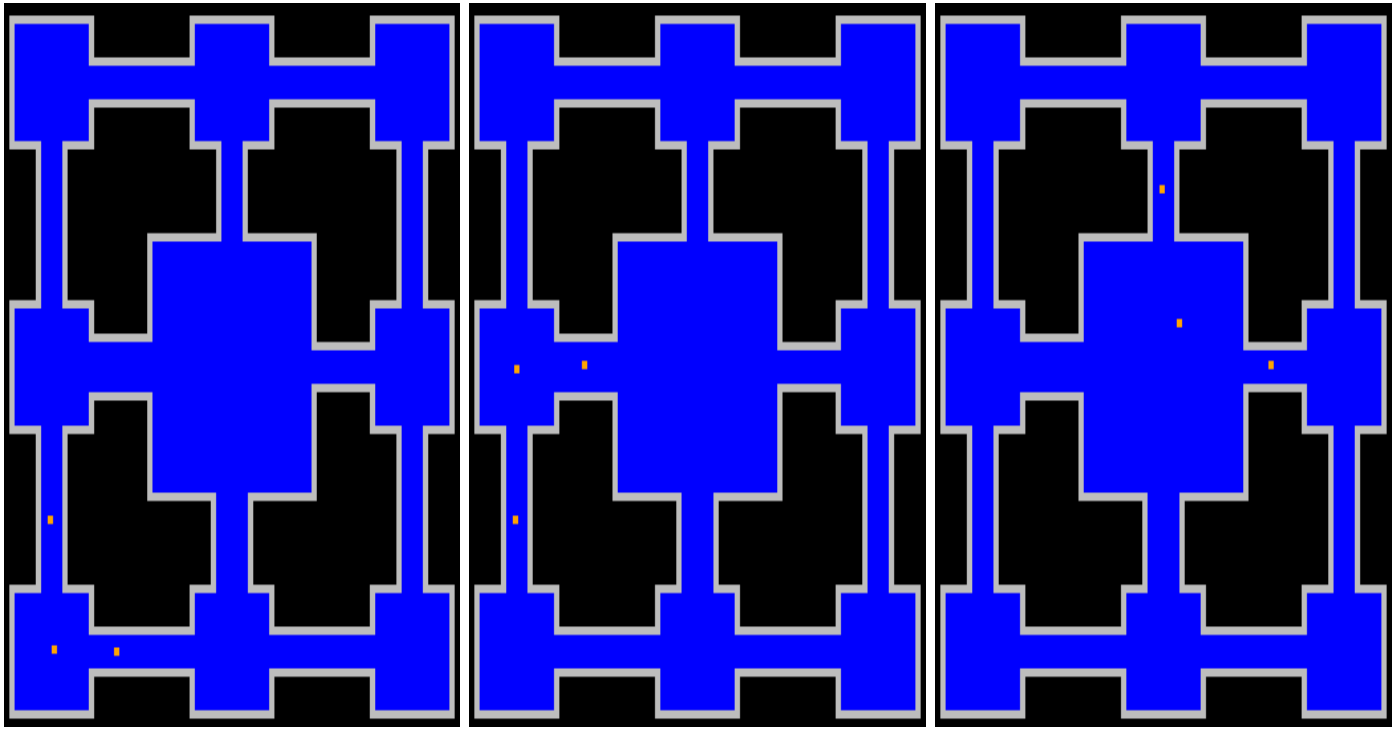
Examples of Motion Coordination

- Surrounding



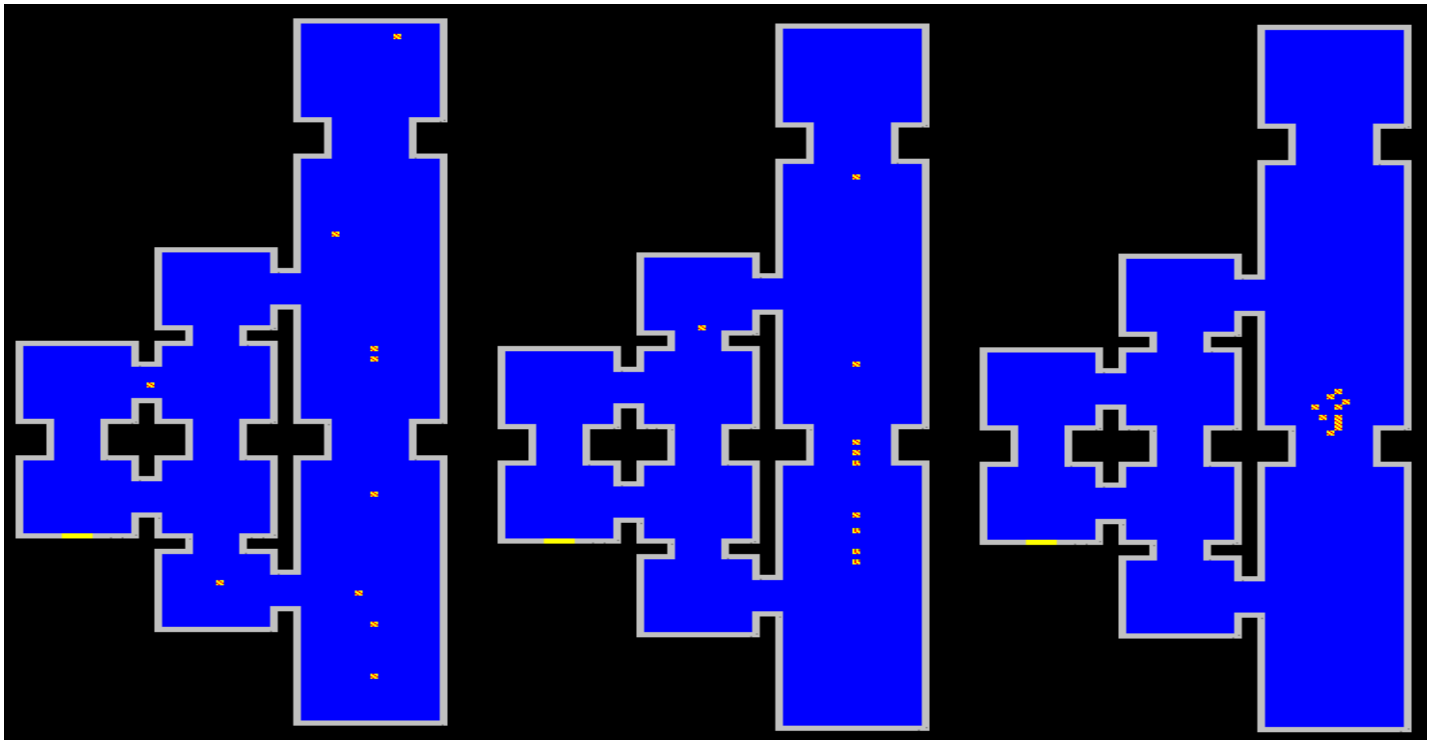
Examples of Motion Coordination

- Moving in Formation



Adaptivity of Motion Coordination

- The algorithms work the same independently of the museum map
  - Without changing a bit in the code of agents
  - E.g., for meetings



Fields in Videogames

- Field-based approaches can be exploited in videogames to drive the actions of characters
  - In "The Sims" fields drive characters toward what they want ("I am hungry!" → let's follow the Fridge field)
  - In Quake, we have integrated field-based motion coordination as a strategy to improve cooperative fighting in the "bad boys" (Mamei and Zambonelli, 2004)

Part 4

- Programming Field-based Coordination

What is Required?

- To program and deploy field-based coordinated application we need
- Some **network infrastructure** to be used as the space in which to propagate fields
  - The Internet, an ad-hoc network, a pervasive network, a sensor network
- A fully distributed **middleware (P2P)**, providing the following minimal services
  - A local dataspace where to store the value of fields as they get propagated, and to have application agents access the local values of fields
  - Communication mechanisms, to have the various middleware communicate with each other and enable propagation of fields in the network
  - System-level event-based mechanisms, to understand how the network situation changes and update fields accordingly
  - Application level event-based mechanisms, to have application agents understand when fields arrive and/or when they change

The TOTA Approach

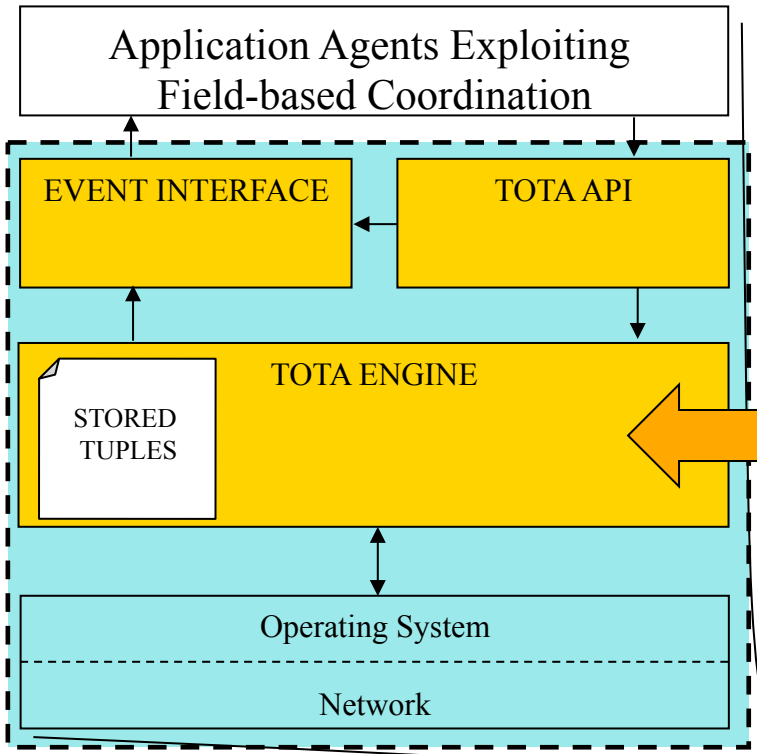
- A tuple-based system for field-based coordination in dynamic networks
  - Implemented for PC, PDAs, Lego Robot
  - Mamei and Zambonelli, 2003-2005
- Extends traditional tuple-based coordination models with a model in which
  - tuples are not stored in a single tuple space
  - Tuples, other than a content ***C*** as usual, can have their own propagation rules ***P***
  - The propagation rule can specify how the content of the tuple can change during propagation

T=(C, P)

TOTA Key Characteristics

- Fields are represented by tuples
  - This enables to include some specific content with fields
  - The programmer can invent and program its own types of fields/tuples
- Tuple libraries are available
  - To exploit with minimal efforts a variety of different types of fields
- Propagation rules are fully programmable
  - This enables programmers to decide how and to which extent a field-tuple should propagate
- Maintenance of the distributed field structure is automatically preserved
  - The middleware automatically react to changes in networks and applications updating the structure of propagated fields/tuples

TOTA Middleware Architecture



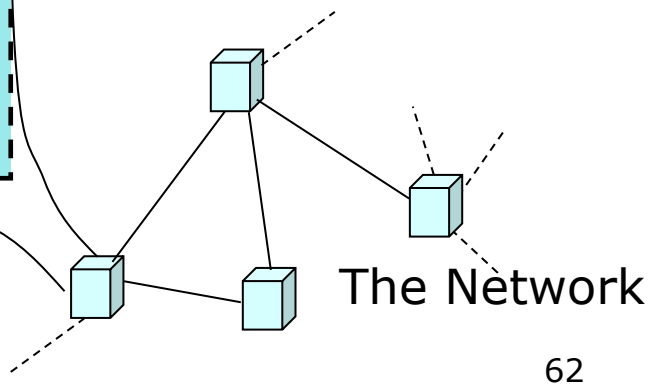
This is used by agents to capture events

This is used to store field-tuples

These are the primitives to access the services of the TOTA middleware

To/From neighbor TOTA middlewares

This structure is replicated in each node of the network



The Network

The TOTA API

```
void     inject (TotaTuple tuple);
// inject a tuple-field in the network
// the middleware will automatically propagate it on the basis of
// propagation rules defined withing the tuple itself

Vector   read (Tuple template);
// read local tuples matching the template

Vector   readOneHop (Tuple template);
// read also the tuples of the neighbourhood, to evaluate gradients

Tuple    keyrd (Tuple template);
Vector   keyrdOneHop (Tuple template);


Vector   delete (Tuple template);
// delete a local tuple

void     subscribe (Tuple template, ReactiveComponent comp, String rct);
void     unsubscribe (Tuple template, ReactiveComponent comp);
// tu subscribe/unsubscribe to event occurring in the tuple space
// related to the arrival or change of field-tuples
```

Programming TOTA Applications

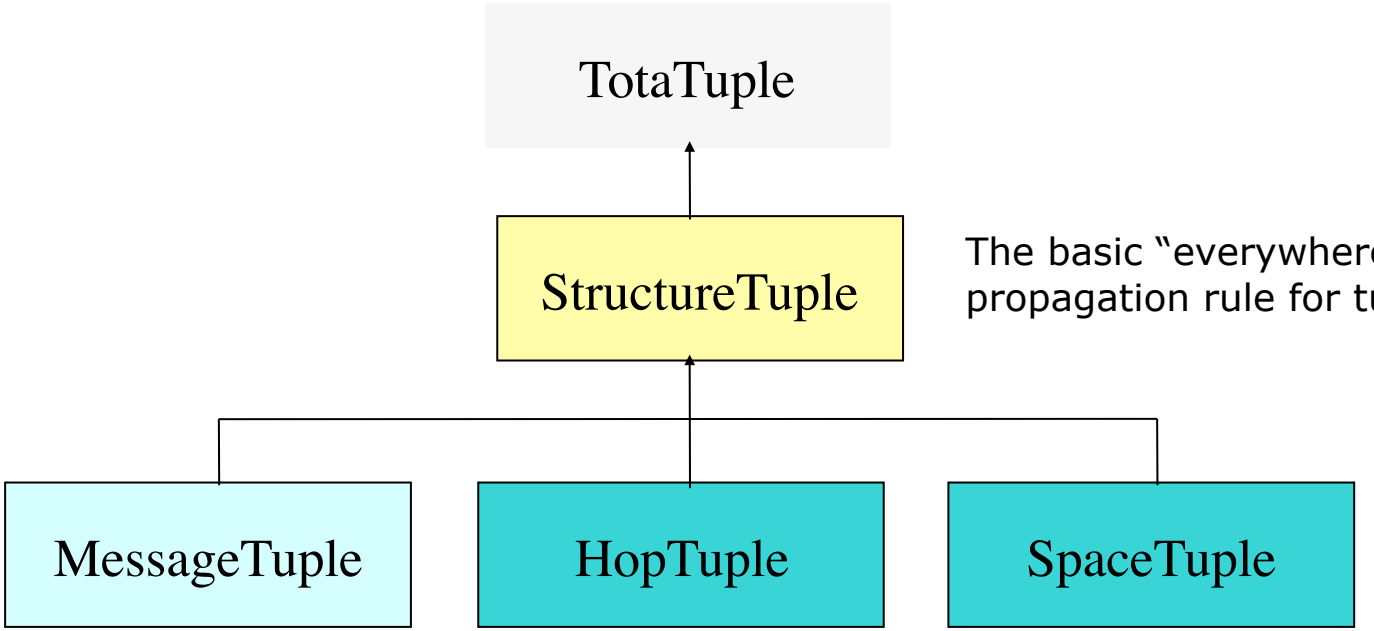
- Programming TOTA coordinated applications basically means to
- Programming the tuples
  - i.e. specifying the tuple classes in terms of the type of content they have to include, their propagation rules, and their maintenance rules
- Programming the agents
  - That is, the code in which agents exploit the TOTA API, create tuple instances and propagate them in the network, and read tuples from the local tuples space

TOTA Tuples

```
abstract class TotaTuple {
protected TotaInterface tota;
/* the state is the tuple content */
public void init(TotaInterface tota) {
// the init method initialize the tuple
this.tota = tota;
}
public abstract void propagate();
// the propagate method is abstract
// has to be implemented by subclasses
// to specify how the tuple should propagate
public void react(String react, String event){
// this method specify how the tuple should
// react, e.g., maintain, in response to
// network dynamic
 }}
```

The TOTA Tuples Library

Partial view of the TOTA tuple hierarchy/library



Tuple Programming

Other than defining its content, programming a tuple may imply programming its propagation rule, which we suggest structuring as below and implementing some of the sub-method specified below

```
public final void propagate() {
 if(decideEnter()) {
  boolean prop = decidePropagate();
  changeTupleContent();
  makeSubscriptions();
  tota.store(this);
  if(prop)
   propagate();
  }
 }
```

The HotTuple Class

Tuple that propagates in the whole network and simply increment a ***hop*** value by one at each hop in the network

```
public class HopTuple extends StructureTuple {
 public int hop = 0;
 public boolean decideEnter() {
  super.decideEnter();
    NMGradient prev =(NMGradient)tota.keyrd(this);
  return (prev == null || prev.hop > (this.hop + 1));
 }
 protected void changeTupleContent() {
  super.changeTupleContent();
 hop++;}}
```

The DownhillTuple Class

A tuple that propagates by following downhill the gradient of an already stored *HopTuple* (it propagates in a single path across the descent of an *HopTuple*)

```
public class DownhillTuple extends StructureTuple {
 public int oldVal = 9999; HopTuple trail;
 public boolean decideEnter() {
  super.decideEnter();
  int val = getGradientValue();
  if(val < oldVal) {
   oldVal = val; return true;}
  else return false; }
 private int getGradientValue() {
  Vector v = tota.read(trail);
  int min = 9999;
  for(int i=0; i<v.size(); i++) {
   HopTuple gt =(HopTuple)v.get(i);
   if(min > gt.hop) min = gt.hop;   }
   return min;}}
```

Programming TOTA Agents

- Let's refer to the example of a tourist in a museum that wants to know where "Mona Lisa" is, and wants to get information about
- The agent in the user PDA
  - inject a Query field in the form of a *HopTuple*, which propagates in the network, and then wait for the income of some Answer tuple
- The agent of the Mona Lisa picture
  - Can be programmed to react to incoming Query tuples
  - By injecting an Answer tuple in the form of a *DownhillTuple* that follows the path of the Query tuple to reach back the user

The UserAgent

```
public class UserAgent implements AgentInterface
{
 private TotaMiddleware tota;

public void start() {
  HopTuple query = new HopTuple();
  query.setContent("Monna Lisa");
  tota.inject(query);
  DownhillTuple answer = new DownhillTuple();
  answer.setContent("Monna Lisa *");
  tota.subscribe(answer,this,"display");
 }

public void react(String reaction, String event) {
  if(reaction.equalsIgnoreCase("display ")) {
  System.out.pritnln("Monna Lisa:" + event); }}
```

The MonaLisaAgent

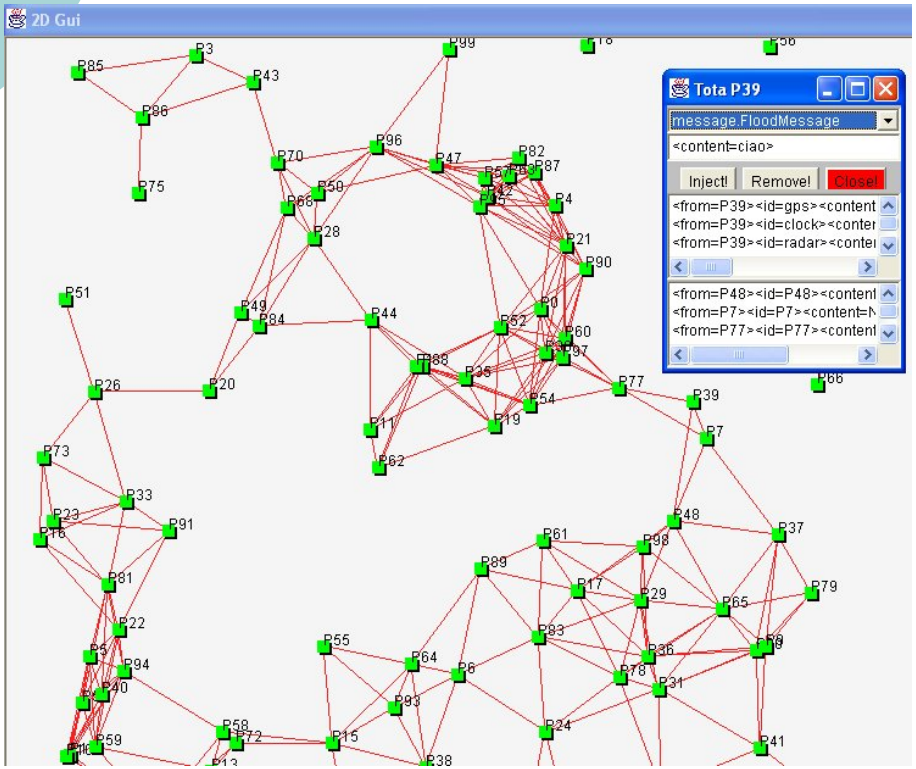
```
public class MonaLisaAgent implements AgentInterface {
 private TotaMiddleware tota;
 private String description, location;

public void start() {
 // subscribe to query. Queries will be conveyed in HopTuple
 HopTuple query = new HopTuple();
 query.setContent(description);
 tota.subscribe(query,this,"answerQuery");
 }

/*code of the reaction, here it injects the answer tuple. The
   answer will be conveyed in a DownhillTuple following the
   query. The query is here referenced as HopTuple event */
public void answerQuery (OneHopIncTuple event) {
  DownhillTuple answer = new DownhillTuple(event);
  answer.setContent(description+" "+location);
  tota.inject(answer);
 }
}
```

A Snapshot of TOTA Implementations

Simulator

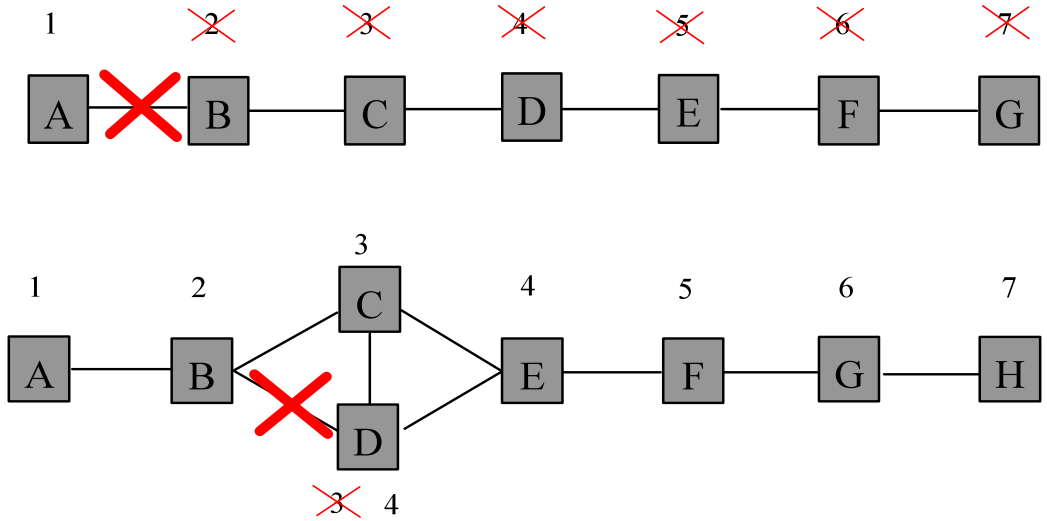


PDA

Lego Robot

Tuple Maintenance

- Tuples must be **propagated** and **maintained**.
- Propagation is based on a simple hop-by-hop epidemic mechanism.
- Maintenance is based on local perception of network events and re-shaping of the propagated structure accordingly



Conclusions and Open Issues

- Field-based coordination as a peculiar form of stigmergy
  - Promoting context-awareness
  - Promoting self-organization
- That finds several useful applications
  - Supporting motion coordination
  - As well as various applications in pervasive computing
- There are several issues that would be worth exploring
  - Exploiting fields for P2P computing
  - Exploiting fields for multiagent coalitions and for computational economies
  - Using computational fields to understand the mechanisms of morphogenesis